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The effect of spruce plantation density on resilience of mixed forests in the Perm Krai

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Abstract: Over the course of the last few decades, many countries across the globe have experienced mass desiccation of spruce plantations. The subject of our research was the spruce forests of the Russian Perm Krai's mixed forest zone. Spruce is a shade–tolerant tree species and low plantation density may adversely affect the spruce health. The aim of this research is to establish how influential the spruce stand density is on causing desiccation in mixed zones in the Perm Krai. The results of an on-site survey which had recorded spruce desiccation in 2017 were analysed. Within the boundaries of the aforementioned forest areas, 2017 saw the desiccation of spruce trees in 301 forest allotments covering an area of 5,343.7 ha. The value of the weighted average category of spruce forest health in Prikamye varies from 2.7 (severely weakened) to 4.2 (desiccating), and the percentage of the volume of spruce deadwood varies from 17% to 59.5%. When the spruce stand density rises from 0.4 to 0.8, spruce stand resilience to desiccation increases.

Keywords: Perm Krai's mixed coniferous-deciduous forest zone; stand density; spruce forest desiccation; spruce forest resilience; weighted average category of health; deadwood volume

Over the course of the last few decades, many countries across the globe have experienced a mass desiccation of spruce plantations (Berg et al. 2006; Schroeder 2007; Müller et al. 2008). Deterioration of forest health and their desiccation is observed all over the world within the borders of the spruce habitat (Sarnatsky 2009).

Research has identified more than 170 reasons for desiccation of spruce plantations (Sarnatsky 2009). Most contemporary authors (Allen et al. 2010; Mezei et al. 2017; Ivantsova et al. 2019) believe that the main reasons for spruce desiccation are drought and eight–toothed spruce bark beetle (*Ips typographus* [L.]) population explosions. Other authors (Meyer 1985; Russmann 1985) believe that the main reasons for spruce desiccation in the European forests include deterioration of needles caused by acid rains and deterioration of roots due to an increase in soil acidity and growth of aluminium and manganese solubility in soil solution. Mezhibovsky (2015) was convinced that the main reason for spruce desiccation is soil contamination by the root fungus (*Heterobasidion annosum* [Fr.] Bref.). At the same time, other authors (Man'ko et al. 2009) link massive desiccation of spruce plantations with natural evolutionary transformations of forest ecosystems and their centuries-long dynamics. Therefore, there is no single opinion on the reasons for spruce desiccation among scientists. This indicated the need for deep research of the issue.

Silvicultural-taxonomic indices relating to spruce plantations exercise a significant influence on stand resilience. In particular, it has been established that spruce plantation resilience is dependent on the

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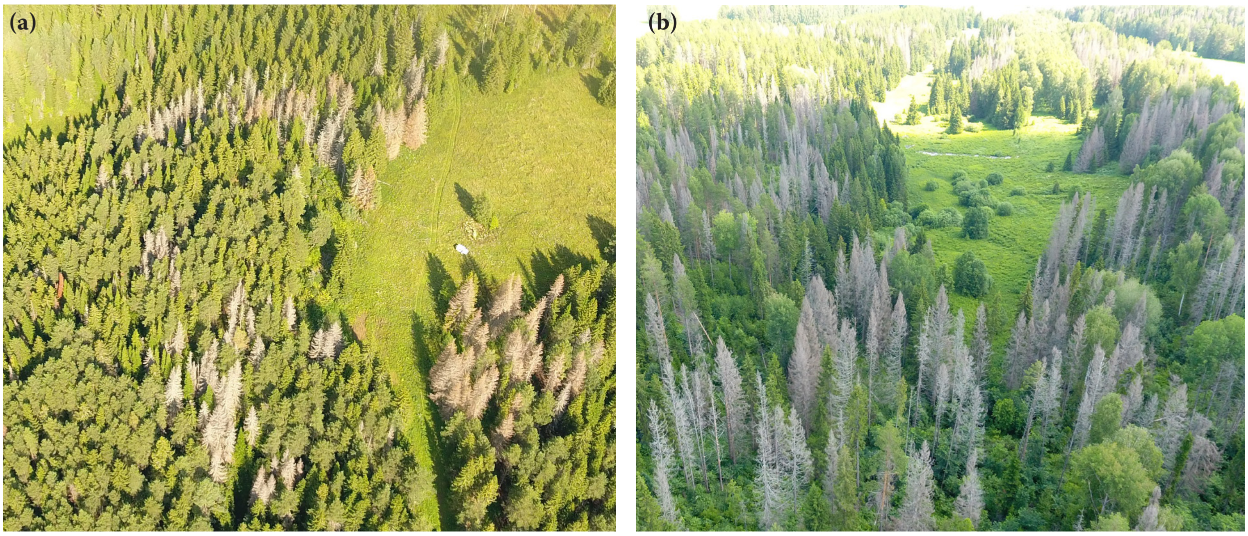

Fig. 1. Group and continuous desiccation of spruce stands: (a) group desiccation of spruce stands, (b) continuous desiccation of spruce stands

type of forest conditions (Ivanchina, Zalesov 2017) as well as on age (Nevolin et al. 2005).

Taxonomic density characterises the compactness of trees in a defined forest plot. Relative density is expressed in tenths of a unit. A unit is taken as a stand density that is maximal for the given species, age and forest conditions over an area of 1 ha. When the relative density is 100% (one unit), the plantation utilizes all the natural resources in the territory covered with trees (Baginsky 2013).

Spruce is a shade-tolerant tree species. A density of 0.8 is optimal for spruce stands (Lugansky et al. 2010). Low stand density and sparseness can have an adverse effect on the health of spruce trees.

In the European part of the Russian Federation, in the Perm Krai's mixed coniferous-deciduous forest zone, mass desiccation of spruce plantations has been observed. Desiccation of spruce plantations in the south of Perm Krai became noticeable around 1945 (Lesnov et al. 1969). Since that time hotspots of spruce desiccation have been emerging constantly. Furthermore, the nature of desiccation is not singular or scattered, but it is group or continuous (Fig. 1).

The direction of our research was determined by the fact that in recent years no studies have been carried out on spruce stand desiccation in the Perm Krai (Ivanchina, Zalesov 2017).

Our research aims to determine the effect of taxonomic spruce stand density on spruce stand health, establishing relations between these indicators in the conditions of the Perm Krai's mixed coniferous-deciduous forest zone.

MATERIAL AND METHODS

Perm Krai is located on the border between Europe and Asia, at the junction of the Russian Plain and the Ural Mountains. A mixed coniferous–deciduous forest zone occupies the southern part of the Perm Krai (Fig. 2). In the territory of the mixed coniferous-deciduous forests of the Permsky Krai the climate is moderately continental. The seasons are characterized by humid cool autumn, relatively short warm summer, quite a long cold winter and late, cool and relatively dry spring (Shklyaev, Balkov 1963).

The spruce plantations located in the Perm Krai's mixed coniferous–deciduous forest zone became the subject of our research. Research was carried out over a vast territory and included five forest areas: the Kishertskiy, Kuedinskiy, Oktiabrskiy, Osinskiy and Tchaikovskiy areas (Zalesov 2017). Total area of the study region is 1,171,767 ha.

The southern part of Perm Krai is dominated by mixed spruce forests. According to the Ministry of Nature of Perm Krai, as per 2017, plantations with a predominance of spruce accounted for 35.3% in the study area (Fig. 3). Birch plantations cover 28.2% of the area. Linden (14%), pine (10%) and aspen (9.6%) plantations occupy a large share of the forests. Other species in the area include grey alder, fir and larch.

Spruce desiccation in the study area occurred from 2012 to 2017, however, the majority of the plots desiccated in 2015. Fieldwork was performed in 2017.

With regard to this, the studied plantations were characterised by significant variation in taxonomic

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Fig. 2. Map-scheme of Perm Krai forest areas (1 : 25 000)

indices: the age of plantations varies from classes 3 to 6 of age, the density from 0.4 to 0.8. The 3rd class of age includes forest stands from 41 to 60 years

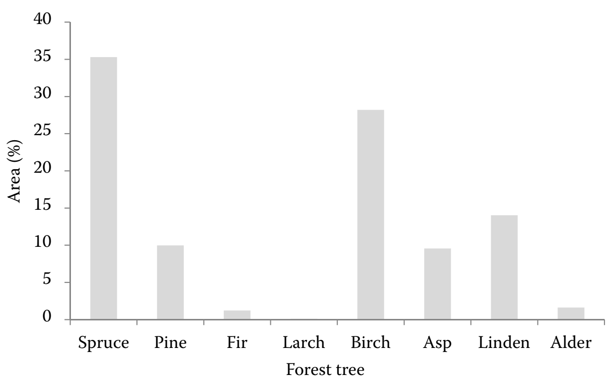

Fig. 3. Percentage of different forest species from the total forest area of the study area

of age (middle–aged plantations), 4th class – from 61 to 80 (premature plantations), 5th class – from 81 to 100 (mature plantations), 6th class – from 101 to 120 years of (mature). Three types of forest growth conditions were covered by the research: relatively poor fresh (B_2), relatively rich fresh (C_2) and relatively rich wet (C_3) (Pogrebnyak 1968). All the plantations are characterised by high productivity (the yield class not lower than III) (Verkhunov 1991). All spruce plantations have a mixed composition of forest stands which includes fir, pine, birch, aspen and linden. Pure spruce stands are absent.

During the research process which was carried out by specialist forest pathologists, sampling plots (SP) were set out in hotspots of spruce desiccation. According to a well-tried and approved methodology, the SPs were set out in rectangles to ensure

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that at least 100 spruce trees were covered (Bynkova et al. 2011). During 2017 301 SP were set out by forest pathologists on the research area. The size of sampling plots set out by forest pathologists varies between 0.33 and 3 ha, and the number of trees studied at each of the SPs varied between 106 and 810. The following indices were defined within the boundaries of each SP:

– The type of forest growth conditions (determined visually with the help of plant indicators);
– Stand density (measured in full metres);
– Individual tree diameter (measured at a height of 1.3 metres using callipers);
– Each tree's health category;
– Height (using an altimeter, 15–20 trees of each species and each tier were measured);
– Age (determined from 15–20 spruce trees with the help of cores taken from the root collars trees with an age drill).

The health category was determined visually according to the following scale (Zalesov et al. 2017):

(I) healthy – trees without signs of damage, with dense canopy and green needles;
(II) weakened – trees with thinned canopy and light green needles;
(III) severely weakened – trees with thin canopy, light green dim needles and fruit bodies of bracket fungi;
(IV) desiccated – trees with very thin canopy, yellowish needles and more than 2/3 of the branches desiccated;
(V) recent deadwood – trees with yellow or red-brown needles, with partially fallen needles;
(Va) recent windfall – fallen trunk with roots broken off, needles present;
(Vb) recent blowdown – tree trunk partially broken, needles present;
(VI) old deadwood – needles absent, bark and twigs partially or completely fallen;
(VIa) old windfall – tree trunk fallen with roots broken off, needles absent, bark and twigs partially or completely fallen;
(VIb) old blowdown ‑ trunk partially broken, needles absent, bark and twigs partially or completely fallen;
(VII) dangerous trees (in need of felling) – trees with structural damage (with hollows or dangerous inclination) which can lead to the fall of the tree.

Forest pathologists calculated the stand average taxonomic indices and defined the timber volume of each species for each health category. The weighted average category of health for each species was determined according to the following Equation 1 (Kovalev 1993):

$$K_{wa} = (P_1 \times K_1 + P_2 \times K_2 + \ldots + P_n \times K_n)/100 \qquad (1)$$

where:
K_{wa} – weighted average category of species health;
$P_{i\text{-}th}$ – percentage of the timber volume of each health category (%);
$K_{i\text{-}th}$ – health category index.

Using the results from the sampling plots, the official reports from the forest pathology surveys were drawn up for each forest area. The form of the report on the forest pathology survey has been approved by the Ministry of Natural Resources and Environment of the Russian Federation's Order № 480 from 16th Sept. 2016 "Procedure for carrying out forest pathological surveys and the form of the act of forest pathological surveys". The reports of the field survey indicate the stand taxonomic characteristics and the volume of spruce wood in each health category, as well as the weighted average health category of each species.

We analysed the field survey reports from 2017. All the plantations were arranged according to age, type of forest growing conditions and stand density. For stands of all densities, the average value of the weighted average category of the species health was defined and, in addition, the average volume of spruce stands in each plantation was calculated.

Stands were evaluated by relative density according to the following scale: low-density stands have a density of up to 0.5 (inclusive); medium-density stands have a density varying from 0.6 to 0.7; high-density stands have a density of 0.8 and above (Lugansky et al. 2010).

Evaluation of stand health was carried out by Kovalev (1993). Stands in the weighted average category of health up to 1.5 were evaluated as healthy, those between 1.6 and 2.5 were assessed as weakened, from 2.6 to 3.5 were seen as severely weakened, from 3.6 to 4.5 were desiccated and higher than 4.5 were evaluated as dead.

To confirm the existence of a relationship between stand density and the weighted average category of spruce tree health, as well as between density and the volume of spruce deadwood in a plantation, a correlation coefficient was determined. All statistical calculations were carried out in the Microsoft Excel (2010, Microsoft) (Baginsky, Lapitskaya 2017).

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Table 1. Number and area of investigated forest allotments (indd·ha^{-1})

Age class	Number and area of forest allotments with plantations of different density					Total
	0.4	0.5	0.6	0.7	0.8	
Relatively poor fresh conditions of forest growing place (B_2)						
3 (41–60 years)	–	2 61.1	9 145.9	11 165.8	2 14.1	24 386.9
4 (61–80 years)	–	7 98.8	21 596	18 252.3	–	46 947.1
5 (81–100 years)	–	2 50	6 70.7	2 13.9	–	10 134.6
6 (101–120 years)	–	2 17.3	–	–	–	2 17.3
Total	–	13 227.2	36 812.6	31 432	2 14.1	82 1485.9
Relatively rich fresh conditions of forest growing place (C_2)						
3 (41–60 years)	2 19.2	8 94.5	17 273.5	31 1210.5	1 16	59 1,613.7
4 (61–80 years)	5 44	11 137	52 852.8	31 368.5	3 13.6	102 1415.9
5 (81–100 years)	1 5.3	6 92.9	10 158.4	4 42.9	–	21 299.5
6 (101–120 years)	1 4.8	2 135.2	2 27	1 12	–	6 179
Total	9 73.3	27 459.6	81 1,311.7	67 1,633.9	4 29.6	188 3,508.1
Relatively rich wet conditions of forest growing place (C_3)						
3 (41–60 years)	–	1 5.6	6 73.4	1 6.7	–	8 85.7
4 (61–80 years)	1 6	5 30.7	5 68	5 36.2	–	16 140.9
5 (81–100 years)	2 25	–	2 65.2	2 29.1	–	6 119.3
6 (101–120 years)	–	1 3.8	–	–	–	1 3.8
Total	3 31	7 40.1	13 206.6	8 72	–	31 349.7
Total						
3 (41–60 years)	2 19.2	11 161.2	32 492.8	43 1,383	3 30.1	91 2,086.3
4 (61–80 years)	6 50	23 266.5	78 1,516.8	54 657	3 13.6	164 2,503.9
5 (81–100 years)	3 30.3	8 142.9	18 294.3	8 85.9	–	37 553.4
6 (101–120 years)	1 4.8	5 156.3	2 27	1 12	–	9 200.1
Total	12 104.3	47 726.9	130 2,330.9	106 2,137.9	6 43.7	301 5,343.7

RESULTS

In 2017 in Kishertskiy, Kuedinskiy, Oktiabrskiy, Osinskiy and Tchaikovskiy forest areas of the Perm Krai, spruce desiccation was recorded in 301 forest allotments over an area of 5,343.7 ha. The largest area of spruce forests desiccated in relatively rich fresh vegetation conditions (188 forest sites over an area of 3,508.1 ha). The largest area of spruce desiccation was observed in plantations in the 4th age category (164 forest sites over a total area of 2,503.9 ha). It should be noted that this type of forest growth conditions and the stand age category are the prevailing type in the Perm Krai's mixed coniferous-deciduous forest zone (Table 1).

Medium-density stands dominate the Perm Krai's mixed coniferous-deciduous forest zone. The density of desiccated spruce stands varies from 0.4 to 0.8.

The weighted average category of spruce health in Prikamye varies from 2.7 (severely weakened) to 4.2 (desiccated) (Table 2).

The highest values of the weighted average category of health occur in low-density stands (values from 4.0 when density is between 0.4 and 0.5). The minimum values of the weighted average category of health are characteristic of medium- and high-density spruce stands (health values of less than 3.0 when density is between 0.7 and 0.8).

With an increase in spruce stand density from 0.4 to 0.8, the values of the weighted average category of health decrease. A particularly clearly established pattern can be observed in the rows where a significant sample has been taken. This pattern is reaffirmed by the high correlation coefficient which demonstrates the extremely close relationship between indices (Table 3). It should be noted that the loss of several values from a row (in C_2 and C_3 type forest growth conditions) is explained by the small sample of forest areas.

The relationship between the density of spruce stands growing in the Perm Krai's mixed coniferous-deciduous forest zone and the state of their health is described by Equation 2:

$$y = 3 \times 10^{-13}x^2 - 1.8x + 4.34 \quad (2)$$

where:

x – stand density,

y – value of the weighted average category of spruce health.

The equation is proved when density is between 0.4 and 0.8. Furthermore, the high value of the coefficient

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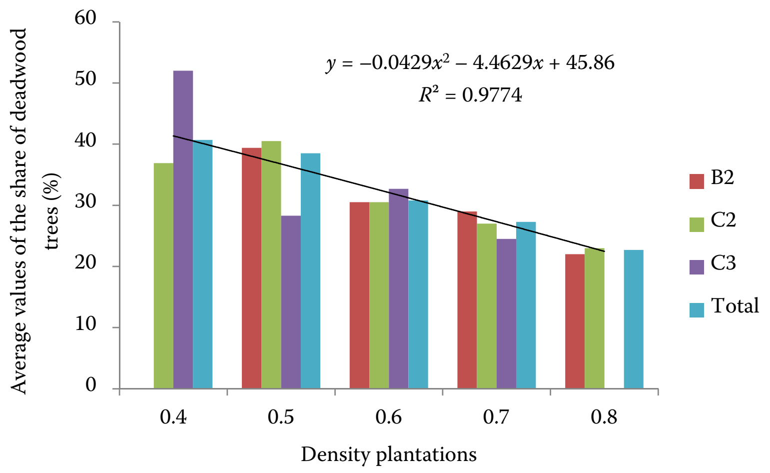

Fig. 4. Average values of deadwood tree share in plantations with various density (%)

of determination (R^2 = 0.976) demonstrates the particularly close relationship between the indices.

Table 2. Mean values of the weighted average categories of sanitary state for plantations of different ages and density

Forest site type	Age class	Mean values of the weighted average categories of sanitary state with density plantations				
		0.4	0.5	0.6	0.7	0.8
B_2	3	–	3.3	2.9	3.1	2.7
	4	–	3.3	3.2	3.0	–
	5	–	4.2	3.6	3.3	–
	6	–	3.4	–	–	–
Total		–	3.4	3.2	3.1	2.7
C_2	3	3.2	3.9	3.3	2.9	3.4
	4	3.7	3.6	3.2	3.2	2.8
	5	3.4	3.4	3.4	3.9	–
	6	2.8	3.1	3.1	3.7	–
Total		3.6	3.6	3.2	3.1	2.9
C_3	3	–	3.7	3.3	3.2	–
	4	3.6	3.0	3.4	3.0	–
	5	4.0	–	3.6	2.7	–
	6	–	3.2	–	–	–
Total		3.8	3.2	3.3	2.9	–
Overall total	3	3.2	3.7	3.2	3.0	2.9
	4	3.7	3.4	3.2	3.1	2.8
	5	3.8	3.7	3.5	3.4	–
	6	2.8	3.2	3.1	3.7	–
Total		3.6	3.5	3.2	3.1	2.9

B_2 – relatively poor fresh conditions of forest growing place, C_2 – relatively rich fresh conditions of forest growing place, C_3 – relatively rich wet conditions of forest growing place

The effect of stand density on spruce desiccation is also proved by the average values of the percentage of spruce deadwood recorded in stands with different relative densities (Fig. 4).

The percentage of spruce deadwood in forest plantations located in the Perm Krai's mixed coniferous-deciduous forest zone varies from 22.0% to 52.0%.

Low-density stands are characterised by a high percentage of deadwood (more than 50% when the stand density is between 0.4 and 0.5). A low percentage of spruce deadwood occurs in medium– and high-density stands (less than 20% when the stand density is between 0.6 and 0.8).

With an increase in the relative density of spruce stands in Kishertskiy, Kuedinskiy, Oktiabrskiy, Osinskiy and Tchaikovskiy forest areas of the Perm Region from 0.4 to 0.8, the percentage of spruce deadwood in the plantations decreases. The dependence between stand density and the percentage of spruce deadwood is proved by high values of correlation coefficients (Table 3).

A dependence between the percentage of spruce deadwood in plantations and stand density is shown by Equation (3):

$$y = -0.0429x^2 - 4{,}4629x + 45.86 \quad (3)$$

where:
x – plantation density;
y – percentage of spruce deadwood (%).

The dependence is confirmed by the high value of the coefficient of determination R^2 = 0.977. The equation is true for stand densities from 0.4 to 0.8.

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Table 3. The values of the correlation coefficient and its estimation

Forest site type	Compared variables	Correlation coefficient	Correlation estimation
B_2	dependence of the weighted average categories of sanitary state on the density of plantations	–0.965	very strong correlation
	dependence of the share of deadwood trees on the density of plantations	–0.969	very strong correlation
C_2	dependence of the weighted average categories of sanitary state on the density of plantations	–0.964	very strong correlation
	dependence of the share of deadwood trees on the density of plantations	–0.915	very strong correlation
C_3	dependence of the weighted average categories of sanitary state on the density of plantations	–0.897	strong correlation
	dependence of the share of deadwood trees on the density of plantations	–0.825	strong correlation
Total	dependence of the weighted average categories of sanitary state on the density of plantations	–0.988	very strong correlation
	dependence of the share of deadwood trees on the density of plantations	–0.988	very strong correlation

DISCUSSION

Several Russian scientists have studied the effect of relative spruce stand density on desiccation. However, their conclusions were drawn from a limited amount of material. According to the findings of Malakhova and Krylov (2012), in the Moscow Region of the Russian Federation it is primarily maturing and mature spruce stands with a density of 0.7 that are subjected to desiccation. Other authors (Maslov 2010) noted that the bark beetle (*Ips typographus* Linnaeus, 1758), whose reproduction is inseparably liked to the process of spruce forest desiccation, prefers to attack medium-density spruce plantations. Zolubas et al. (2009) believed that the probability of bark beetle spruce damage occurrence grows with the increase in the sum of the cross–sectional areas of spruce trees. Jakus et al. (2011) was of a similar opinion, namely that spruce forests desiccate in areas with a higher density.

The pattern of the effect of density on the health of spruce forests is outlined in an article by Klishina (2015). The author set out three sample plots with relative densities of 0.6, 0.7 and 0.8. The weighted average category of spruce forest health constituted 2.67, 2.47 and 1.91, respectively. However, the author did not consider any dependence.

Soviet scientists revealed that spruce health improved with an increase in tree density (Atrokhin, Ievin 1985). The research of the Soviet scientists indicated that in the naturally forming spruce plantations the current growth rate increased with the growing sum of cross-sectional areas, and reached its maximum with the maximum density.

As we have already noted, most researchers link massive spruce desiccation with global warming. According to the Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change "Climate Change 2013: The Physical Science Basis", global warming has been around since the 1950s (Stocker et al. 2013). However, according to the authors' information (Skuhravy 2002), in the countries of Western Europe, for instance, the chronicle of massive spruce desiccation has been kept since 1473.

Before 1950 the average air temperature in the study area was 1.3°C and annual precipitation amounted to 500 mm (Shklyaev, Balkov 1963). Climate data in recent years is provided by the Perm Centre for Hydrometeorology and Environmental Monitoring. In recent years the average air temperature (Fig. 5) has varied from 1.4°C (2013) to 6.1°C (2010). Precipitation has varied from 221.4 to 20,176.2 mm per year (Fig. 6). The year 2010 was abnormally hot, but the process of spruce deterioration has continued until now.

The indicated facts allow claiming that spruce desiccation is not caused merely by climate. In addition, as we cannot change the climate, we are trying to find a way to preserve spruce forests in the existing climate.

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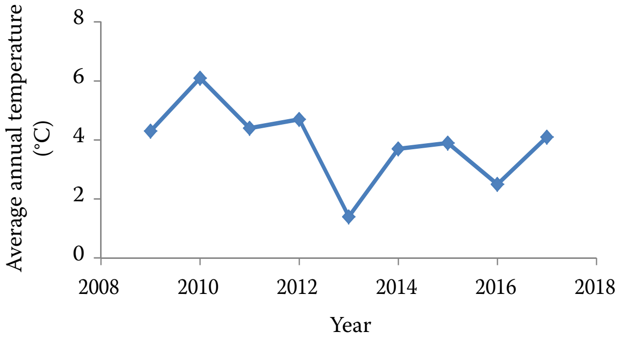

Fig. 5. Average annual temperature in the study area for 2009–2017

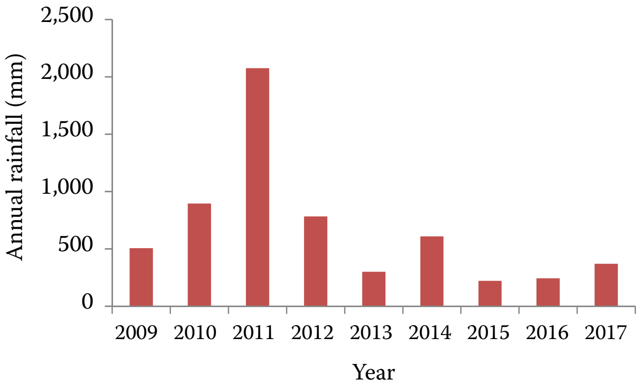

Fig. 6. Annual precipitation in the study area for 2009–2017

Some authors suggest replacing spruce with other wood species, e.g. larch, oak and pine (Baginsky, Lapitskaya 2009). Currently, forest larch is bred in Belarus. In the study area, the share of larch does not exceed 0.1% (Fig. 6), which indicates that this species is not suitable for Prikamye. Pine accounts for about 10%. The prevailing type of habitat conditions in Prikamye is C_2 (Ivanchina, Zalesov 2017), which is more suitable for pine growing. In the current conditions, pine will be less productive. We believe that it is impossible to replace spruce with other species completely. It is crucial to find a way to preserve spruce forests.

CONCLUSIONS

Summing up, the density of forest stand along with other taxation specifications of growing stock (type and age of forest) are among many factors that influence the resilience of spruce forests in Prikamye to desiccation. However, density of forest stand is not the main reason for spruce desiccation.

We have established a pattern whereby the spruce plantation resilience grows along with an increase in relative density. This pattern will allow for the minimisation of the spruce desiccation process with the help of silvicultural interventions. It is important to consider the effect of spruce plantation density on desiccation when determining the appropriate form of felling. In particular, the relative stand density should not fall below 0.6 during voluntary selective felling. Moreover, it is our opinion that selective sanitary felling should not be carried out if the relative density of the stand section set aside for rearing drops to 0.4 or lower. If this occurs, it is more expedient to prescribe clear sanitary felling followed by reforestation.

At the same time, the importance of the problem at hand for forestry makes it necessary to continue researching the given area using more extensive material. The problem of massive spruce desiccation requires comprehensive research with raising finance from multiple sources and attracting specialists in various disciplines.

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